MONTHLY TECHNICAL PROGRESS REPORT
DESIGN, DEVELOPMENT, AND FABRICATION OF A REACTION WHEEL UTILIZING A BRUSHLESS DC MOTOR

CONTRACT NO. NAS 5-9016

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APPROVED BY:

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TO:

GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

FROM:

SPERRY FARRAGUT COMPANY
DIVISION OF SPERRY RAND CORPORATION
BRISTOL, TENNESSEE

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SECTION I

INTRODUCTION

This is the first of a series of monthly technical progress reports covering the design, development and fabrication of four reliable, efficient, lightweight, sealed brushless DC reaction-wheel systems for Goddard Space Flight Center as described in Goddard Space Flight Center Specification No. 67-33 dated 4 March 1964.

The reaction-wheel is to be hermetically sealed for operation in hard-vacuum environments. It will be driven by a two-speed brushless DC motor with constant-torque-limiting from 0 RPM up to 250 RPM and will have provision for speed control by means of a pulse-width-modulated signal. Also, the motor is to provide a signal output proportional to speed. The goals for this program are described in detail in Goddard Specification No. 67-33, "Reaction Wheel with Electrically Commutated DC Torque Motor Drive".

This report covers the period from 1 July through 30 July, 1964 and deals with Phases I and II of the project, i. e., motor and wheel design, and commutator design. Work on these two phases is to be completed by December, 1964. Phase III, the manufacture of four reaction-wheel systems, is to be completed by 1 April 1965.

SECTION II

FOREWORD

Engineering efforts during this reporting period, as described in the body of this report, have been concentrated in the following areas:

1. Motor Design

   Analytical evaluations have been made of two approaches, the torquer concept and the ironless motor concept. In the former, the rotor contributes an insignificant portion of the required inertia. In the latter method the rotor magnets would provide a major portion of the total inertia. Both concepts would utilize electronic commutators.

2. Wheel and Housing Design (for use with torquer)

   Calculations have revealed that the initial approach considered for the wheel and housing would result in exceeding the target value for over-all weight. These calculations were based on the use of a "pancake" motor configuration for the drive.

3. Commutator Design

   The possibility of increasing the efficiency of the electronic commutator by using extra stator windings is being investigated.

SECTION III

TECHNICAL PROGRESS

A. MOTOR DESIGN

1. Torquer Concept

The torquer design is the standard mechanical configuration for a pancake motor with a winding to permit electronic commutation. Originally, an even number of slots per pole pair was used to maintain the usual winding method. After it was determined that an odd number of slots could be properly wound, 63 slots were used to materially reduce cogging torque.

The magnetic friction torque will be greater than the specified value of .005 ft-lb. A friction torque of .03 ft-lb. is assumed for the calculations in this report.

The stator (inner member) was designed for the use of Vanadium Permendur. A saturation density greater than that of silicon steel permitted a reduction in predicted weight from seven pounds to less than three pounds. The lamination and winding are optimized for an operating flux of 22,000 lines per pole, although the rotor (outer member) is capable of a higher flux. By grinding the outer diameter, the magnet area-to-length ratio may be changed to obtain a maximum energy product. This will also reduce the weight, since it is expected to produce a final diameter of 5.0 inches.

The unit efficiency is compatible with requirements of 30 watts maximum input for 0.5 ft-lb of torque at 250 RPM.

Two motor windings are used for the dual speed capability, and a third winding is available for a tachometer output. The 250 RPM winding occupies 75% of the available slot space, the 1000 RPM winding 20%, and the tachometer winding 5%. The number of conductors associated with the respective speeds are:

$$Z_{1000} = 882 \text{ conductors}$$

$$Z_{250} = 2710 \text{ conductors}$$

$$Z_{Tach} = 3780 \text{ conductors maximum}$$

The motor design characteristics are:

a. 250 RPM Winding:

Back EMF = $6.93\ n \times 10^{-2}$; n = RPM

Resistance = 4.17 ohms

Torque Output = 0.5 lb-ft from 0 to 250 RPM

Voltage = 24

Current = 1.25 amp max.

b. 1000 RPM Winding:

Back EMF = $2.17\ n \times 10^{-2}$

Resistance = 1.63 ohms

No Load Speed = 1000 RPM

Voltage = 24

Current = 1.25 amp max.

c. Tachometer Winding:

The maximum AC output voltage gradient is $9.67\ n \times 10^{-2}$ volts. However, this requires #40 wire. A lesser output would permit use of larger and less fragile wire.

. Engineering drawings for magnets and stator laminations have been completed and the parts are on order.

2. Ironless Motor Concept

At the suggestion of Goddard, a motor was investigated using the ironless (printed-circuit) motor concept. The field circuit rotates and provides the major portion of the required inertia. A printed-circuit stator was not practical due to the limited number of conductors possible. A wound circuit card has been designed and will be fabricated to determine the feasibility of the configuration. Two main advantages result from the ironless-motor concept. The majority of the motor weight is used to provide the inertia, thus reducing over-all weight of the unit. Also, the friction torque is quite small since no magnetic material is present in the wound member. For this reason, the efficiency of such a motor would be higher than what could be achieved with the torquer design.

Three windings are also used here, with operating design characteristics similar to the torquer.

The motor design characteristics are:

a. 250 RPM Winding:

Back EMF = $6.93\ n \times 10^{-2}$

Resistance = 2.98 ohms

Torque Output = 0.5 lb-ft from 0 to 250 RPM

Voltage = 24

Current = 1.25 amp. max.

b. 1000 RPM Winding:

Back EMF = $2.17\ n \times 10^{-2}$

Resistance = 1.16 ohms

No Load Speed = 1000 RPM

Voltage = 24

Current = 1.25 amp. max.

c. Tachometer Winding:

The maximum AC output voltage gradient is 0.202 n volts using number 40 wire. For ease of construction, a larger wire size and a reduced output is preferable. Figure 1 shows the various magnet configurations proposed for the ironless motor. A high leakage flux exists between the poles on the first two methods shown in (a) and (b) of Figure 1. This leakage path is eliminated by the third method, (c) thus producing more available flux. Also, more usable space is available for magnet material since the magnets are not separated by a non-magnetic material as in the first two configurations.

The winding of this motor is described in more detail under the heading, "Coil Winding for Ironless Motor".

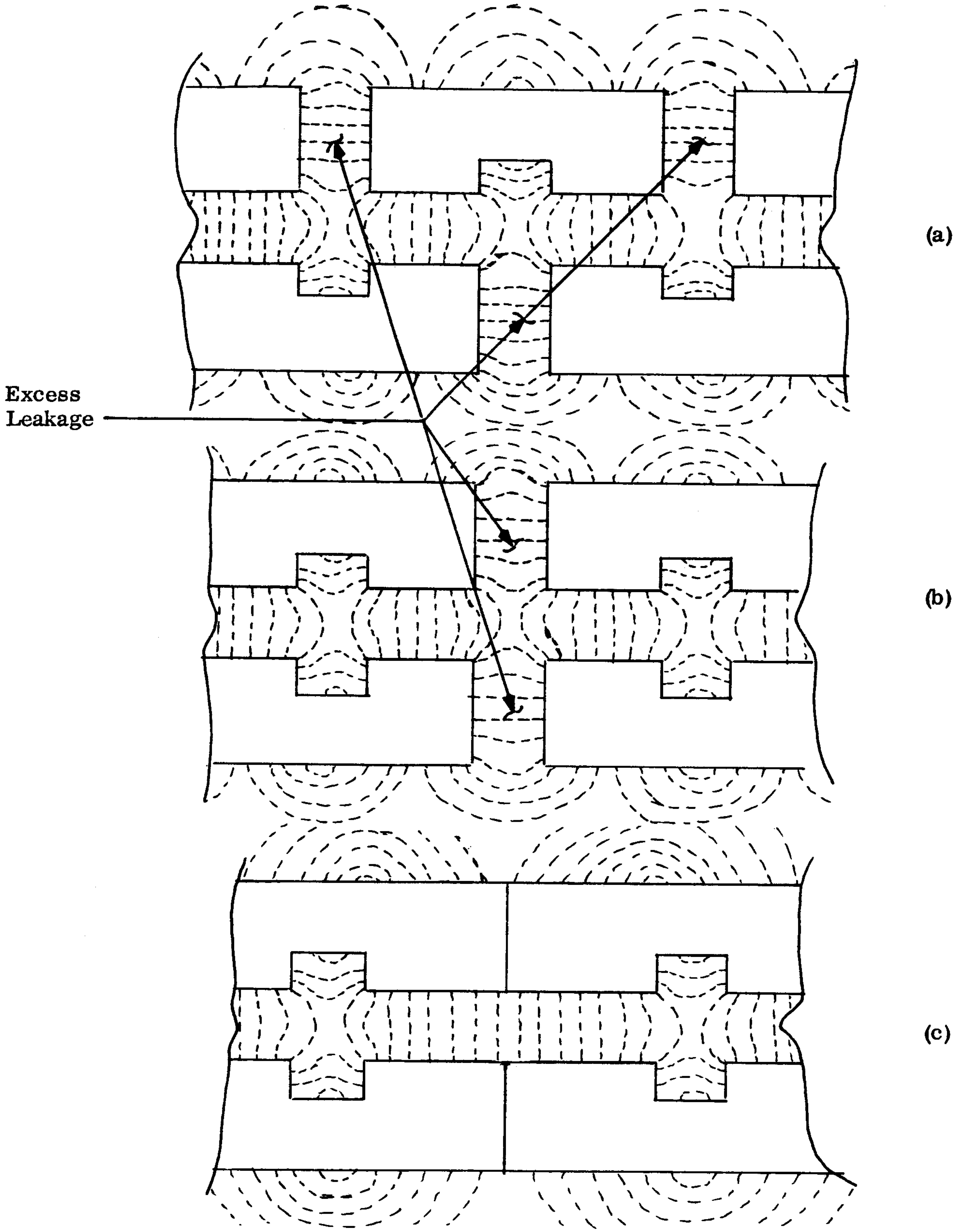

FIGURE 1

PROPOSED MAGNET CONFIGURATION FOR IRONLESS, BRUSHLESS DC MOTOR

Drawings for the stator and rotor have been completed and the parts are on order. The stator will be fabricated by Sperry Farragut Company, but the magnets have been ordered from an outside vendor.

B. WHEEL AND HOUSING DESIGN FOR TORQUER CONCEPT

Preliminary calculations indicated the following weights and inertias for the Reaction-Wheel System using the torquer concept:

Field	1.42 lbs.	0.0522 lb-ft.^{2}
Stator	1.36 lbs.	
Flywheel	5.3 lbs.	1.21 lbs-ft.^{2} (neglecting supports)

The weight of the flywheel, less supports, is based upon a maximum O.D. of 11.5 inches and a width of 3.5 inches. Therefore, the weight of housing, flywheel supports, bearings, and electronic packaging must be 1.92 pounds or less to stay within the over-all weight requirement of 10 pounds. It should be noted that supports for the flywheel will add inertia which will decrease the required weight of the flywheel by an amount somewhat less than the weight of the supports.

The following calculations apply to an hermetically sealed cylinder with flat end plates, unsupported except at the ends, and fabricated from T6 aluminum. Its internal pressure is assumed to be 14.7 psia. A cylinder-wall thickness of 0.093 inch and plate thickness of 0.156 inch would result in a maximum combined meridional stress of 35,745 psi if the sealed cylinder were placed in a hard vacuum. This would give a factor of safety of 1.12 for the wall strength, and the weight of the housing would be 4.8 pounds. To increase the factor of safety to 2.5 the cylinder wall would have to be increased to 0.156 inch.

Because the calculations mentioned above have indicated that the weight of a conventional cover would be too high, at least in conjunction with the torquer design, an effort has been initiated to redesign the cover in such a manner that it will not have to be hermetically sealed. Two limitations must be considered in such a design:

1. The air drag on the wheel should never alter the characteristics of the wheel. Although the operational design of the wheel is for hard-vacuum applications, the air drag must not have an adverse effect on the performance characteristics of the wheel.

2. No oil vapors should escape from the container and contaminate the environment outside of the reaction wheel package. To prevent the vapors originating from bearing lubrication from escaping into the vehicle, a thin-walled shell would be built around the reaction wheel. A breathing passage would be included in this shell to assure that there was not any pressure differential across the shell. This feature of the proposed design would result in the desired reduction in weight because of the reduced strength requirement. It would be necessary to have a filter in the breathing passage that would prevent the contaminating vapors from escaping. Proper application of Millipore filter paper promises to accomplish the restriction of vapors without impairing the necessary exchange of air. If this design approach proves feasible, an over-all reduction in weight of the system would be accomplished.

C. STATOR-COIL FOR IRONLESS MOTOR

If the stator-coil were wound like a flattened toroid on a single washer-shaped form, those portions of the winding that are in apposition, on opposite faces of the stator, would be carrying current in opposite senses. Then the reaction forces exerted on the two rings of magnets of the rotor would tend to make them counter-rotating. To avoid this, we will attempt to produce a winding that is skewed at its periphery so that opposite pairs of conductors will produce identical reaction forces in both rings of the rotor.

A preliminary investigation was made to determine whether the concept of a skewed winding was feasible from a manufacturing standpoint. Two basic approaches are being studied.

1. The coils are laid and varnished individually into their final skewed configurations on two ring-shaped circuit boards. This method promises to be the most accurate but would be very difficult to wind and would probably require a guide between the two circuit boards in the winding.

2. In the second method, the coils are wound without skew on the ring-shaped forms. The coils are then skewed by angular displacement of the top plane of the coil with respect to the bottom plane. This angular rotation is about an axis passing through the centers of the two coil forms and normal to their faces.

A choice between the above methods will not be made until both have been tried on a developmental basis. Consideration will be given to other methods that might show promise.

D. COMMUTATOR DESIGN

The exact features that must be incorporated in an electronic commutator for this project have yet to be determined. However, the breadboard model described in Appendix I has characteristics that are sufficiently promising to warrant further consideration. The gain in efficiency obtained by this approach for some motor designs, would far outweigh the slight increase in production costs and the insignificant decrease in reliability.

In addition to the requirements of Specification No. 67-33, "Reaction Wheel with Electrically Commutated DC Torque Motor Drive", the following stipulations apply as a result of a telecon between Mr. P. Studer and Mr. R. Kincer.

1. A control signal of ±24 VDC will be provided from an external source with an output impedance of 20 K ohms. The polarity of the signal will determine the sense of rotation of the drive shaft.

2. Speed will be determined by a +28 VDC pulse-width-modulated control signal to be supplied from an external source with an output impedance of 5 K ohms. The modulation will vary between 3% and 90%. This upper limit of 90% is an amendment replacing the value of 97% specified in Goddard Specification No. 67-33. It will necessitate the introduction of a new design. A constant torque of 0.5 lb-ft is now required at 250 RPM at 90% modulation.

E. RELIABILITY

All of the design concepts for this system are being evolved with the aim of achieving a reliability of 92% for a lifetime of three years at an average power level of 10% of rated power. This reliability figure is based on operation in an earth-orbiting satellite with an ambient temperature range of $-10^{o}C$ to $+70^{o}C$.

F. IMMINENT ENGINEERING EFFORTS

1. Breadboard Motor (Torquer)

A breadboard motor will be built utilizing the torquer concept. Development work will refine the initial design.

2. Ironless Motor

a. Stator

A wound circuit card for the stator of the printed-circuit-motor concept will be fabricated and evaluated.

b. Rotor

Efforts are now being directed toward fabricating a rotor and designing tooling for magnetizing of its permanent magnets.

3. Housing

a. General Comments

Since calculations indicated that the initial housing design probably would yield an overweight system, at least in the case where the torquer drive would be used, attempts are being made to design a lighter housing. New shapes and materials will be considered. These may include ribbed designs in addition to the concept of a thin-walled cylinder with a negligible pressure differential across it.

b. Thin-Walled Cylinder Concept

In connection with the thin-walled-cylinder approach, calculations will be made to predict the amount of drag on the wheel when it is operated at atmospheric pressure. The significance of this drag will be evaluated further after its magnitude is estimated. The application of Millipore filters will be investigated further for possible use with the thin-wall housing.

SECTION IV

ADMINISTRATIVE STATUS

A. SCHEDULE

To date, none of the problems encountered has been so unusual as to indicate excessive difficulty in meeting the contracted schedule.

B. PERSONNEL

No change in personnel has been made on this project since its inception, and none is contemplated at this time.

C. FUNDING

The funding of this project is being reviewed critically and will be discussed in detail in the next monthly report.

R. D. Kincer
R. D. Kincer
Project Engineer

APPENDIX I

REACTION WHEEL TORQUER DESIGN

REACTION WHEEL TORQUER DESIGN

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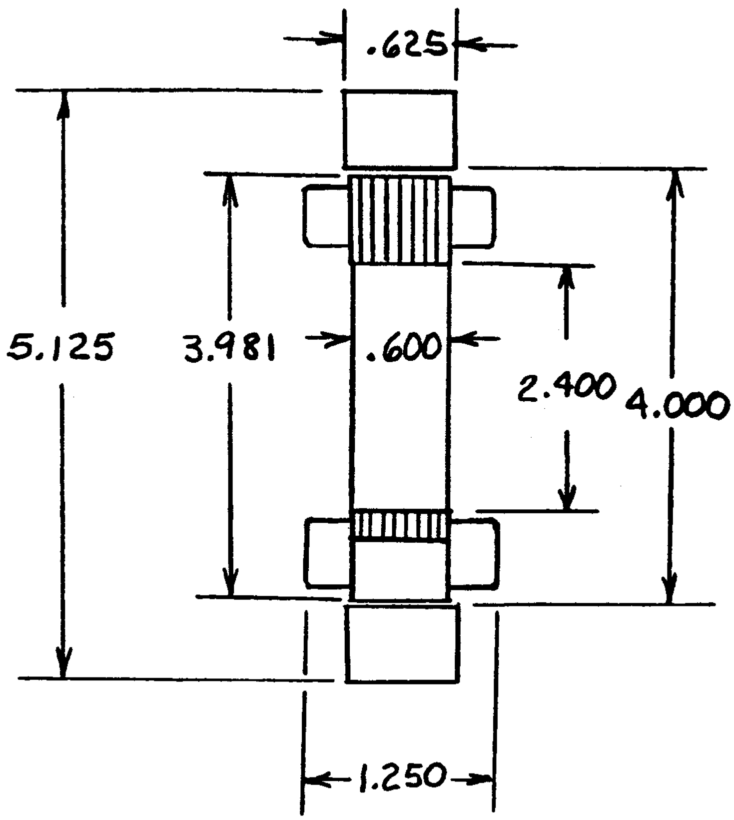
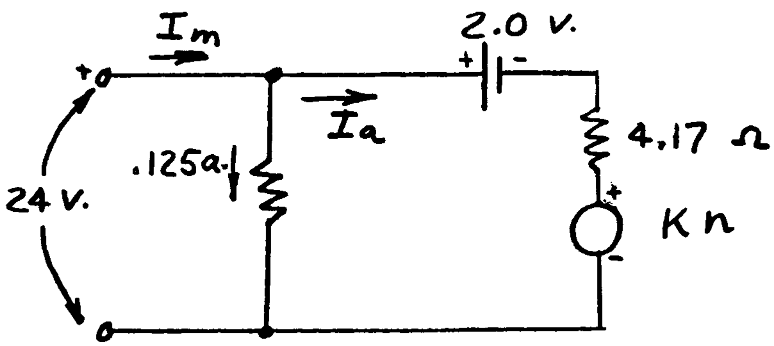
I/ ASSUMPTIONS

$P = 14$ POLES
$N_t = 63$ TEETH
$g = .0095$ AIR GAP



THE EQUIVALENT CIRCUIT OF THE MOTOR AND COMMUTATOR IS ASSUMED TO BE



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$P_{IN} = 30$ WATTS MAX.

AT 250 RPM

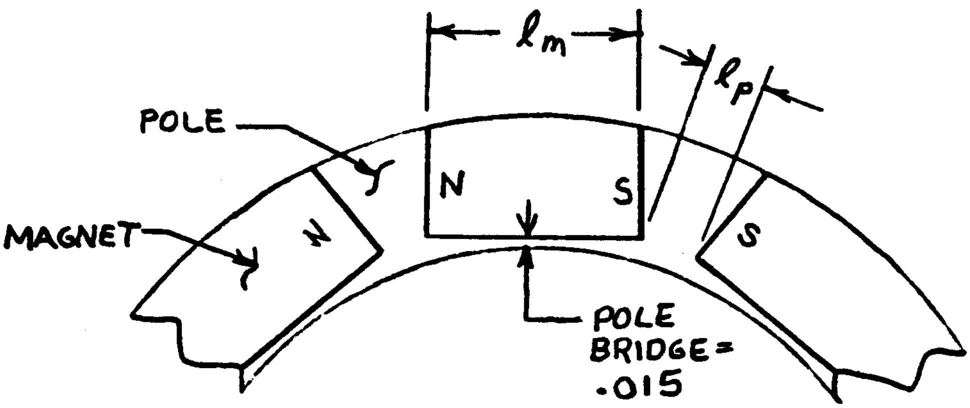
$$I_m = \frac{30}{24} = 1.25 \text{ a.}$$

$$I_a = 1.125 \text{ a.}$$

$$24 = 2 + 4.17(1.125) + Kn \qquad n = 250$$

$$K = 6.93 \times 10^{-2}$$

II/ TO DETERMINE THE FIELD OPERATION



ASSUMING A USABLE FLUX OF 25,000 LINES/POLE IN INGOT IRON OPERATING AT A FLUX DENSITY OF 90,000 LINES/IN²

$$\ell_p = \frac{B}{\phi \, \ell} = \frac{25000}{90{,}000 \times .625} = .445$$

$$\ell_m = \frac{\pi D}{P} - \ell_p = .460$$

THE EFFECTIVE POLE ARC IS APPROXIMATELY 65% OF ONE POLE PITCH

$$\text{POLE ARC} = \frac{\pi D}{14} \times .65 = .583 \text{ IN.}$$

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$$PERMEANCE = \frac{\ell_s \times POLE\ ARC}{g} = 36.8$$

$$\frac{B}{H} = \frac{PERMEANCE}{\frac{M_A}{4M_L}} = 19.7$$

M_A = AREA OF MAGNET FACE

THE CONSTANT "4" IS USED SINCE TWO MAGNETS SUPPLY ONE POLE, BUT ONLY HALF THE LENGTH IS ASSOCIATED WITH EACH POLE.

FROM THE CURVE FOR ALNICO V B, THE MAGNET DENSITY IS 10 K GAUSS.

$$\phi_{MAX} = B(2M_A) = 43,300 \text{ LINES}$$

HOWEVER, THE POLE BRIDGE WILL BE SATURATED AND WILL SHUNT THE FLUX ϕ_B

$$\phi_B = B_{SAT}\, A_b = 130,000(.015 \times .625) = 1220 \text{ LINES}$$

LEAKAGE AND RELUCTANCE EFFECTS REDUCE THE AVAILABLE FLUX BY APPROXIMATELY 25%, THUS THE MAXIMUM USABLE FLUX IS

$$\phi'_{MAX} = .75(43,300) - 1220 = 31,280$$

DUE TO IMPERFECT MAGNETIZATION, KEEPERING EFFECTS, AND A RESERVE SAFETY FACTOR, A FINAL FLUX PER POLE OF 22000 LINES WILL BE USED.

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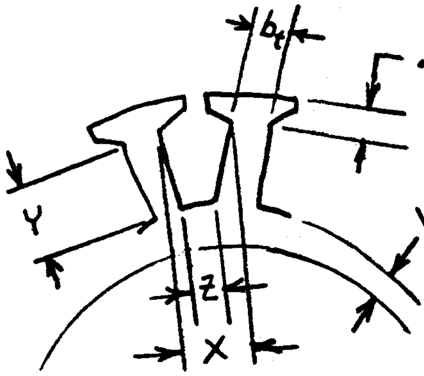
III/ TO DETERMINE A LAMINATION CONFIGURATION



MAT'L: VANADIUM PERMENDUR
$B_{teeth} = 130{,}000$ LINES/IN²
$B_{CORE} = 121{,}000$ LINES/IN²

$$\text{TEETH/POLE} = t_p = \frac{\text{POLE ARC}}{\tau_{sp}} = 2.92$$

$$b_t = \frac{\phi}{B \ell_s \, t_p} = \frac{22000}{130{,}000 \times .600 \times 2.92} = .097$$

$$h_c = \frac{\phi}{2 \ell_s B} = \frac{22000}{.600 \times 2 \times 121{,}000} = .151$$

$$y = \frac{O.D. - 2(.025) - 2h_c - I.D.}{2} = .615$$

$$z = \frac{[I.D. + 2h_c]\pi}{\text{NO. TEETH}} - b_t = .038$$

$$x = \frac{[O.D. - 2(.025)]\pi}{\text{NO. TEETH}} - b_t = .099$$

$$A_{SLOT} = \frac{(x+z)Y}{2} = .0421$$

IV/ TO DETERMINE 250 RPM WINDING

$$A_{WIRE} = A_{SLOT}(\text{FILL FACTOR})(\%\text{ FOR 250 RPM})$$

$$A_{WIRE} = .0421(.34)(.75) = .01067$$

$$\frac{Z\phi P}{2\times 60} n\times 10^{-8} = Kn$$

$$Z = \frac{6.93\times 10^{6}\times 60}{22000\times 7} = 2710$$

$$Z_{SLOT} = \frac{2710}{63} = 43$$

$$A_{COND} = \frac{A_{WIRE}}{Z_{SLOT}} = 2.48\times 10^{-4}$$

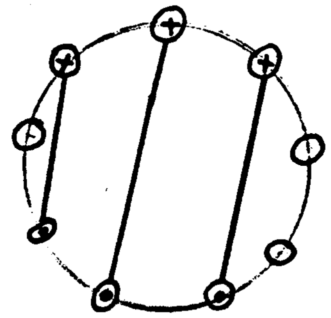
$$DIA_{WIRE} = \sqrt{\frac{4A_{COND}}{\pi}} = .0178$$

#26 HF WIRE $\rho = 49.9\ \Omega/1000\text{ ft.} @ 75°C$

$$\ell_c = \ell_s + \frac{\pi D_{AVE}}{P} + 1.250 - \ell_s = 1.67\text{ IN.}$$

$$R = \frac{2}{9}\rho\,\ell_c Z = \frac{2\times 49.9\times 1.67\times 2710}{9\times 12\times 1000} = 4.17\text{ ohms}$$

TO REDUCE RIPPLE, AN ODD NUMBER OF TEETH HAS BEEN CHOSEN. THE WINDING CONFIGURATION PER PAIR OF POLES IS SHOWN FOR SIMPLICITY. (ONE PHASE)



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V/ TO DETERMINE COMPATIBILITY WITH EFFICIENCY REQUIREMENTS

$P_{IN\ MAX} = 30$ WATTS

$P_{OUT} = .00074\,Tn = .00074(.5)(192)(250) = 17.8$ WATTS

$P_{LOSS} = P_{IN} - P_{OUT} = 12.2$ WATTS MAX.

THE FRICTION TORQUE WILL be LESS THAN .03 Lb.-ft. DUE TO HYSTERESIS AND ROTATIONAL TORQUE.

SUMMATION OF KNOWN LOSSES:

$$\begin{aligned} P_{I^2R} &= 5.27 \text{ WATTS} = (1.125)^2(4.17) \\ P_{COM} &= 5.25 \text{ WATTS} = 2(1.125) + 24(.125) \\ P_{ROT} &= \underline{1.06} \text{ WATTS} = .00074(.03)(192)(250) \\ &\quad 11.58 \end{aligned}$$

THUS, THE BEARING TORQUE MUST BE LESS THAN

$$T = \frac{12.2 - 11.58}{.00074(250)} = 3.35 \text{ OZ-IN}$$

WHICH IS CONSERVATIVE.

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VI/ TO DETERMINE 1000 RPM WINDING

$$A_{WIRE} = A_{SLOT}(FILL)(\% \text{ FOR } 1000 \text{ RPM})$$

$$A_{WIRE} = .0421(.34)(.20) = .00286$$

ASSUMING R = 1.6 OHMS AND A POWER INPUT DUE TO LOSSES OF 8 WATTS

$$I_a = \frac{8}{24} - .125 = .209 \text{ a.}$$

$$24 = 2 + 1.6(.209) + Kn$$

AT 1000 RPM

$$K = .0217$$

$$\frac{Z\phi P}{2 \times 60} n \times 10^{-8} = .0217\,n$$

$Z = 844$ BUT, TO WIND $Z = 882$

$$Z_{SLOT} = 14$$

$$A_{COND} = \frac{.00286}{14} = 2.04 \times 10^{-4}$$

$$DIA_{WIRE} = \sqrt{\frac{A_{COND}\,4}{\pi}} = .0161$$

#27 WIRE $\rho = 62.5\,\Omega/1000$ ft @75°C

$$R = \frac{2 \times 62.5 \times 1.67 \times 882}{4 \times 12 \times 1000} = 1.63 \text{ ohms}$$

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VII/ TO DETERMINE TACHOMETER WINDING

$$A_{WIRE} = .0421(.34)(.05) = 7.15 \times 10^{-4}$$

USING No. 40 HF WIRE

$$A_{40} = \frac{\pi D^2}{4} = 11.9 \times 10^{-6}$$

$$Z_s = \frac{7.15 \times 10^{-4}}{1.19 \times 10^{-5}} = 60$$

$$Z = 60(63) = 3780$$

OUTPUT VOLTAGE = $9.67\, n \times 10^{-2}$ VOLTS

NATURALLY, ANY LESSER VOLTAGE GRADIENT WITH HEAVIER WIRE MAY BE USED.

VIII/ TO DETERMINE WEIGHT

$$V_{FIELD} = \frac{.625\pi}{4}\left[(5.125)^2 - (4.000)^2\right] = 5.05 \text{ IN}^3$$

THE STATOR WEIGHT IS APPROXIMATED BY A SOLID RING OF STEEL THE SIZE OF THE LAMINATION STACK.

$$V_{STATOR} = \frac{.600\pi}{4}\left[(3.981)^2 - (2.4)^2\right] = 4.75 \text{ IN}^3$$

$$\text{WEIGHT} = (5.05 + 4.75).283 \text{ Lb/IN}^3 = 2.77 \text{ Lb.}$$

APPENDIX II

REACTION WHEEL "PRINTED CIRCUIT" MOTOR

REACTION WHEEL "PRINTED CIRCUIT" MOTOR

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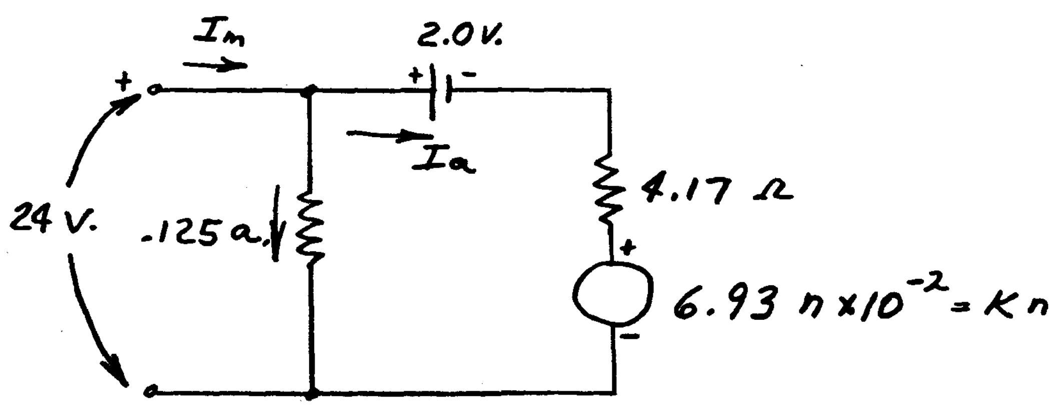
DESCRIPTION:

THE MOTOR IS SIMILAR IN CONSTRUCTION TO A PRINTED CIRCUIT MOTOR, HOWEVER THE FIELD ROTATES AND FORMS THE MAJOR INERTIA FOR THE FLYWHEEL. THE STATOR CONSISTS OF WINDINGS RATHER THAN A PRINTED CIRCUIT. THESE WINDINGS ARE ATTACHED TO A STATIONARY BOARD AND ARE POSITIONED IN THE RADIAL AIR GAP.

I/ ASSUMPTIONS

$P = 30$ POLES
$g = .250$ AIR GAP
ROTOR O.D. = 11.0 IN.
ROTOR I.D. = 10.0 IN.

THE EQUIVALENT CIRCUIT IS ASSUMED TO BE (250 RPM)



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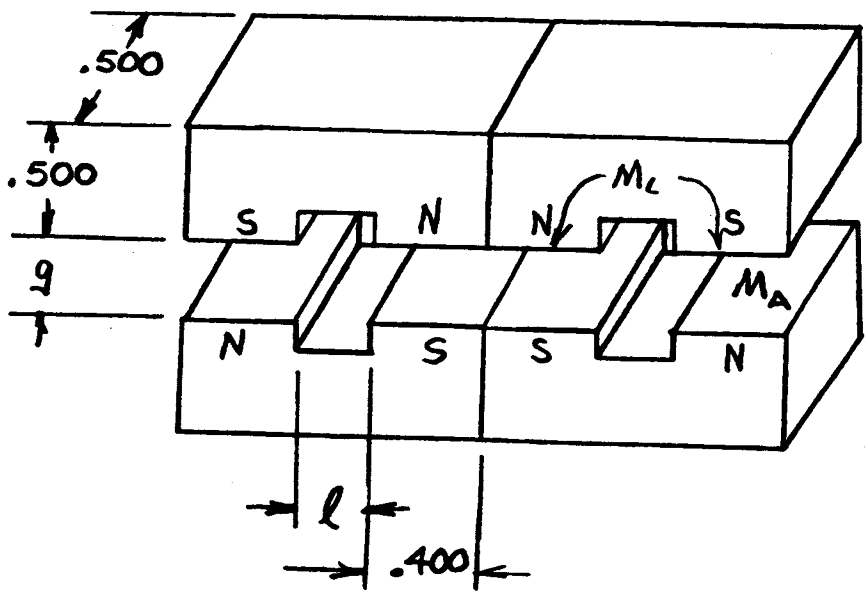
II/ TO DETERMINE THE FIELD OPERATION

DUE TO EXCESSIVE LEAKAGE FLUX IN PREVIOUSLY PROPOSED CONFIGURATIONS, THE FOLLOWING CONFIGURATION IS USED. A PORTION OF THE SUPPORTING MEMBER IS ALSO REPLACED BY ACTIVE MAGNET MATERIAL.



$$l = \frac{(I.D.)\pi}{P} - 2(.400) = .247$$

$$\text{PERMEANCE} = \frac{A_g}{g} = \frac{.4 \times .5}{.250} = 0.8$$

AREA
$A_g = M_A$

$$\frac{B}{H} = \frac{\text{PERMEANCE}}{\frac{M_A}{M_L}} = \frac{0.8}{\frac{.2}{1.25}} = 5.0$$

FROM THE CURVE FOR ALNICO VIII, $B = 4.7$ KGAUSS

IN APPLICATION, IT WILL BE DESIRABLE TO AIR STABILIZE THE MAGNETS, THEREFORE THE MAGNET OPERATING POINT IS

$$\frac{l}{D} = \frac{M_L}{2\sqrt{\frac{M_A}{\pi}}} = \frac{1.25}{2\sqrt{\frac{.20}{\pi}}} = 2.48$$

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FROM THE INDIANA GENERAL CURVE (MANUAL NO. 6A p. 10) FOR AIR STABILIZATION

$$\frac{B}{H} = 8$$

THEREFORE AIR STABILIZATION IS PERMISSIBLE, AND AN OPERATING DENSITY OF 3.5 KGAUSS IS ASSUMED.

$$\phi = BA = 3.5(6.45)(.5 \times .8)10^3 = 9040 \text{ LINES/POLE}$$

III/ TO DETERMINE 250 RPM WINDING

A CLEARANCE BETWEEN THE WINDINGS AND FIELD OF .025 WILL BE ASSUMED.

$$A_{SPACE} = (g - .050)\frac{\pi D}{P} = .200\left(\frac{10\pi}{30}\right) = .2095 \text{ IN}^2$$

$$A_{WIRE} = A_{SPACE}(ff)(\% \text{ FOR } 250 \text{ RPM})$$

$$A_{WIRE} = .2095(.34)(.75) = .0535 \text{ IN}^2$$

$$\frac{Z \phi P}{60a} \cancel{K} \times 10^{-8} = K\cancel{K}$$

$$Z = \frac{6.93 \times 10^{-2} \times 120}{9040 \times 30 \times 10^{-8}} = 3090$$

$$Z_{POLE} = \frac{3090}{30} = 103$$

$$A_{COND} = \frac{A_{WIRE}}{Z_{pole}} = 5.19 \times 10^{-4}$$

$$DIA_{WIRE} = \sqrt{\frac{4 A_{COND}}{\pi}} = .0257$$

#23 H.F. WIRE $\rho = 24.8\ \Omega/1000$ ft. @ 75°C

$$l_c = .5 + .5 + \frac{10.5\pi}{30} = 2.1 \text{ IN.}$$

$$R = \frac{2}{9}\rho Z l_c = \frac{2 \times 24.8 \times 3090 \times 2.1}{9 \times 12 \times 1000} = 2.98\ \Omega$$

IV TO DETERMINE COMPATIBILITY WITH EFFICIENCY REQUIREMENTS

P_{IN} = 30 WATTS MAX

P_{OUT} = 17.8 WATTS

P_{LOSS} = 12.2 WATTS MAX.

SUMMATION OF KNOWN LOSSES:

$$P_{I^2R} = 3.78 \text{ WATTS} = (1.125)^2(2.98)$$
$$P_{COM} = \underline{5.25} \text{ WATTS} = 2(1.125) + 24(.125)$$
$$9.03$$

THUS, THE BEARING AND FRICTION TORQUE MUST BE LESS THAN

$$T = \frac{12.2 - 9.03}{.00074(250)} = 17.1 \text{ OZ-IN.}$$

WHICH PERMITS MORE MARGIN THAN THE TORQUER VERSION, AND A HIGHER EFFICIENCY COULD BE EXPECTED.

V TO DETERMINE 1000 RPM WINDING

$$A_{WIRE} = A_{SPACE}(ff)(\% \text{ FOR } 1000 \text{ RPM})$$

$$A_{WIRE} = .2095(.34)(.2) = .0142 \text{ IN}^2$$

$$\frac{Z\phi P}{60a} n \times 10^{-8} = .0217 n \quad \text{(REF. TORQUER DESIGN)}$$

$$Z = \frac{.0217 \times 120}{9040 \times 30 \times 10^{-8}} = 960$$

$$Z_{POLE} = \frac{960}{30} = 32$$

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$$A_{COND} = \frac{A_{WIRE}}{Z_{POLE}} = 4.43 \times 10^{-4}$$

$$DIA_{WIRE} = \sqrt{\frac{4 A_{COND}}{\pi}} = .0238 \text{ IN.}$$

#24 WIRE $\rho = 31.2\ \Omega/1000 \text{ ft. @ } 75^\circ C$

$$R = \frac{2}{9} \rho Z \ell_c = \frac{2 \times 31.2 \times 960 \times 2.1}{9 \times 12 \times 1000} = 1.16 \text{ ohms}$$

VI/ TO DETERMINE TACHOMETER WINDING

$$A_{WIRE} = .2095(.34).05 = 3.56 \times 10^{-3}$$

USING NO. 40 H.F. WIRE

$$A_{40} = \frac{\pi D^2}{4} = 11.9 \times 10^{-6} \text{ IN}^2$$

$$Z_{SLOT} = \frac{A_{WIRE}}{A_{40}} = 299$$

$$Z_{TOT} = 299(30) = 8970$$

OUTPUT VOLTAGE = .202 n VOLTS

A LESSER VOLTAGE GRADIENT WHICH WOULD USE LARGER WIRE IS RECOMMENDED, SINCE THIS WOULD PRODUCE 202 VOLTS AT 1000 RPM.

VII/ TO DETERMINE THE WEIGHT OF THE ROTOR

THE WEIGHT CALCULATED IS ONLY THE MAGNET WEIGHT. A SUPPORTING STRUCTURE WILL HAVE ADDITIONAL WEIGHT TO MEET THE DESIRED INERTIA.

$$V_{MAGNET} = 2\left(\frac{.5\pi}{4}\right)\left[(11)^2 - (10)^2\right] = 16.5 \text{ IN}^2$$

$$WEIGHT = 16.5 \text{ IN}^2 (.283 \text{ Lb/IN}^3) = 4.67 \text{ Lb.}$$

APPENDIX III

DUAL WINDING COMMUTATOR FOR A BRUSHLESS DC MOTOR

DUAL WINDING COMMUTATOR FOR A BRUSHLESS DC MOTOR

A. OPERATION

A commutating circuit using two motor windings has been investigated. The purpose of this circuit is to reduce the commutator voltage drop and the resulting power loss to a minimum. The circuit is shown in Figure III-1 and functions as follows:

The current through the LS-600 light sensor causes a sufficient voltage to be dropped across the 510K resistor to forward bias Q_1 and cause Q_1 to conduct. The collector current flowing in Q_1 reduces the potential at the base of Q_2 sufficiently to cause Q_2 to turn on. The emitter current flowing in Q_2 and through the 300 ohm resistor reduces the potential at the base of Q_3 and turns Q_3 on. When Q_3 turns on, its base current is added to the emitter current in Q_2. When light impinges on the photo sensor which turns on Q_{14}, the collector current in Q_2 flows through the secondary windings and through Q_{14}. The emitter current in Q_{14} turns on Q_{15} so that the collector current of Q_3 flows through the primary windings and through Q_{15}. The current through the secondary winding produces a magnetic field which adds to the field produced by the current through the primary windings.

The stator, ENG 4007, used for this experimental motor was wound with 285 turns of #34 single Formvar wire for the primary and 285 turns of #44 heavy Formvar wire for the secondary. The equivalent resistances of the primary and secondary windings are 43.2 ohms and 417 ohms respectively. The current through the secondary winding is approximately one-tenth of the primary current. The ten to one ratio of current provides the proper base current drive for Q_{15} and Q_3 to operate at a forced beta of 10.

With the rotor magnetized to run at approximately 3000 RPM with a 40 ma input current, the motor characteristics in Figure III-2 were obtained. Lamp losses were included in the efficiency curve, even though the starting circuit and lamp were not in the circuit, by adding 46 milliwatts to the input power. Comparison of these characteristics (see Figure III-2) with the characteristics of the motors built for Goddard under Contract NAS 5-3582 (see Final Report) yields no appreciable difference between the two types of motors. However, many factors are involved which have not as yet been adequately investigated to prove that the comparison is valid. It can be shown theoretically that a savings of 50-70 milliwatts of power should be realized at the operating point of $P_{in} = 1.0$ watt.

B. PERFORMANCE

The currents through the primary and secondary winding were measured at several different motor loads to determine how the current was dividing between the two windings. The voltage drop across the transistors Q_2, Q_3, Q_{14}, and Q_{15}, were measured at different motor loads. The resulting currents and voltages are shown below.

Total Motor Current (milliamps)	Primary Current (milliamps)	Secondary Current (milliamps)	Collector-Emitter Voltage (volts); V_{ce} (Sat) Q_2	Q_3	Q_{14}	Q_{15}
40	37	2	.03	.06	.02	.07
100	90	7	.06	.075	.03	.07
210	190	18	.1	.09	.09	.08
355	320	30	.12	.11	.09	.1
420	380	40	.14	.12	.14	.125

The circuit was designed so that the transistors would be in saturation at currents up to a stall current of 400 ma. The actual stall current turned out to be greater than 500 ma; however, the circuit was able to handle this current due to safety factors used in design.

The commutator circuit was built from another breadboard and diodes CR1 and CR2 were inadvertently left in the circuit. The power loss across these diodes at 40 ma motor current was approximately 60 milliwatts. Had these diodes been removed from the circuit, the efficiencies would have been higher.

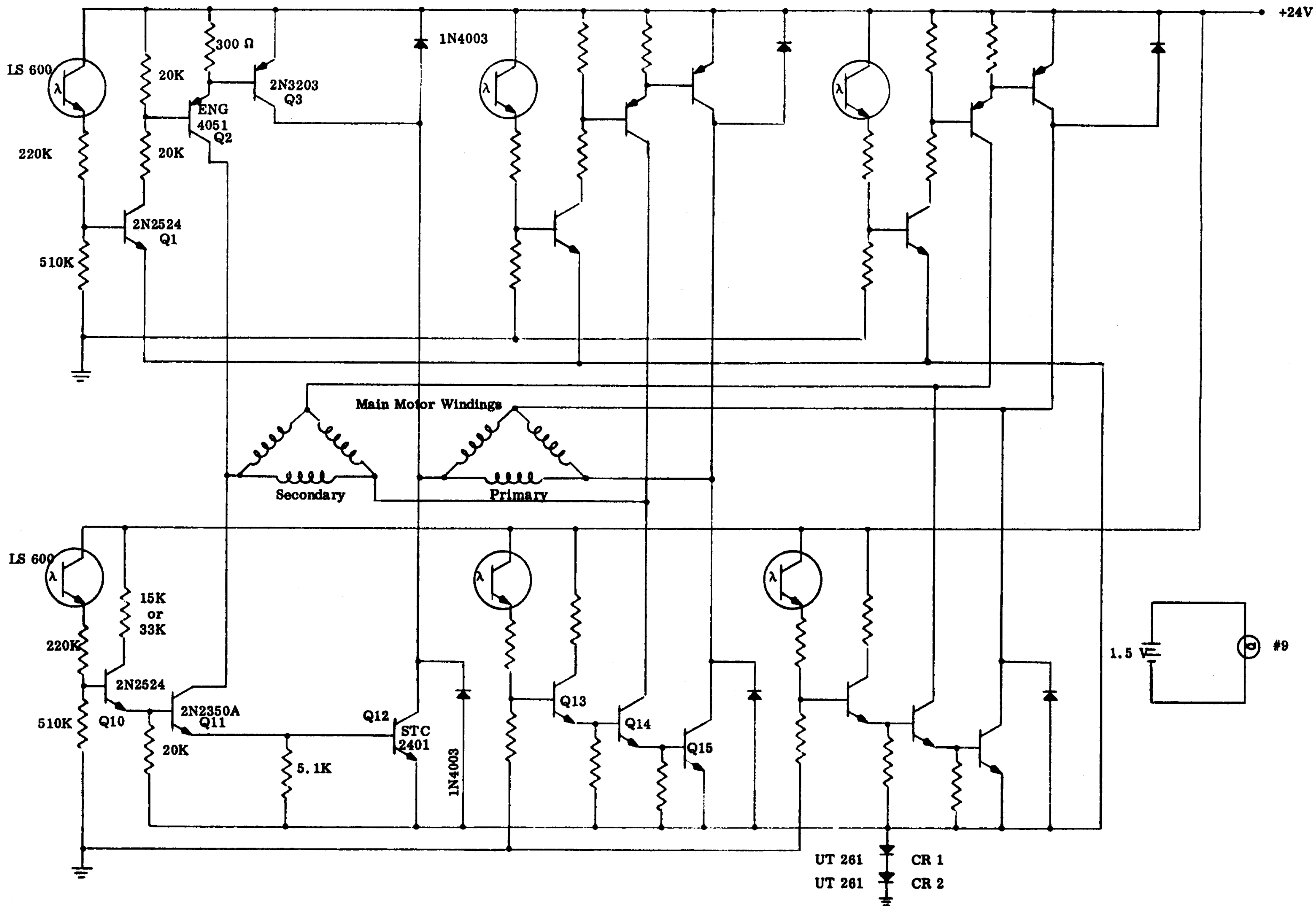

FIGURE III-1

CIRCUIT DIAGRAM OF DUAL-WINDING COMMUTATOR

FIGURE III-2

TEST DATA
BRUSHLESS DC MOTOR

Serial No. Breadboard of Dual-Winding Motor
Input Voltage ____

TESTED BY K. Sells TEST DATE 7-30-64